

## PULSE POWER SUPPLY DEVICE USING RECOVERED MAGNETIC ENERGY

### TECHNICAL FIELD

The present invention relates to a pulse power supply device for supplying pulse current to an inductive load.

### BACKGROUND

When a large electric current is supplied to an inductive load, pulse power supply devices, in which normally an energy source capacitor charged with high voltage is connected to the load by using switches such as an ignitron, a discharge gap switch and a thyristor so that a capacitor discharge is started, are generally used.

In these discharge switches, diodes called clamp circuits are generally connected to loads in parallel or to capacitors in parallel. After the electric current becomes maximum, capacitor voltage is inverted and simultaneously the diodes are turned on, and the load current reflows to the diodes. As a result, reverse charging of the capacitor is prevented, and the clamped electric current continuously flows while being attenuated with time constant  $L/R$  due to electric resistance of the load.

On the other hand, in the applications of the pulse current, frequently rise time is more important than an attenuated waveform. Pulse high-magnetic field bending magnets of compact medical synchrotron accelerators and the like do not use the maximum magnetic field but require an operation such that the magnetic field is raised with time. For this reason, it is demanded that the electric current is attenuated quickly and a pulse rate is heightened. Further, gas excitation laser power supply requires high speed rise of a

voltage and high repetition, and thus high repetition control is required as discharge power supply.

In order that the rise of the discharge current is stopped by controlling switches when the discharge current reaches a necessary current value, switches are switched from those only for ON control such as an ignitron, a discharge gap switch and a thyristor to semiconductor switches having self arc-suppressing ability using a gate signal such as a GTO thyristor and an IGBT (Insulated-gate Bipolar Transistor).

An inductive current on the load side, however, is clamped at a voltage of 0, and is only attenuated by the diodes at long time constant  $L/R$  in a freewheeling state. The energy is wasted and time to wait for the attenuation is required, thereby raising a technical problem of the pulse power supply devices requiring increased capacity and high repetition.

What is needed is a pulse current generating power supply which has high energy efficiency so that wasted energy is reduced and high repetition can be realized.

## SUMMARY OF THE INVENTION

In a first embodiment disclosed herein, a pulse power supply device for supplying a bipolar pulse current to an inductive load with high repetition and for recovering residual magnetic energy of a system so as to use it for a next discharge comprises: a bridge circuit including a first pair of two inverse-conductive semiconductor switches and a second pair of two inverse-conductive semiconductor switches; an energy source capacitor connected to a DC terminal of the bridge circuit; and a control circuit for controlling the first and second pairs of the inverse-conductive semiconductor switches positioned diagonally on the bridge circuit so that when the two inverse-conductive semiconductor switches in the first pair are controlled to turn on simultaneously or alternately, the control circuit controls the two inverse-conductive semiconductor

switches in the second pair to be off, and so that when the two inverse-conductive semiconductor switches in the second pair are controlled to turn on simultaneously or alternately, the control circuit controls the two inverse-conductive semiconductor switches in the first pair to be off; wherein the inductive load is connected to an AC terminal of the bridge circuit.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagram explaining an embodiment of the present invention;

Fig. 2 is a diagram explaining a basic principle of the present invention;

Fig. 3 is a diagram explaining a sequence of an electric current, a voltage and switches in Fig. 2;

Fig. 4 is a diagram explaining a basic principle of bidirectional current of the present invention; and

Fig. 5 is a model diagram of a calculator simulation for analyzing a basic principle of a method of supporting a capacitor voltage, and a simulation waveform of a load current and the capacitor voltage of the present invention.

#### DETAILED DESCRIPTION

Fig. 2 is a diagram explaining a basic operation of the present invention. A power supply side has a constitution of a current switch of a snubber energy recovering system. A capacitor which temporarily stores snubber energy corresponds to an energy source capacitor of the present invention. The current switch of the snubber energy recovering system is disclosed in Japanese Patent Application Laid-Open No. 2000-358359 "FORWARD AND BACKWARD DIRECTION CURRENT SWITCH FOR RECOVERING SNUBBER ENERGY" (Patent Document 1). The present invention utilizes the constitution of the above-mentioned current switch for recovering the snubber energy, but the Patent Document 1 describes the current switch for temporarily storing magnetic energy of a breaking current circuit into a snubber capacitor and discharging it

into a load at the time of next energizing. On the contrary, the present invention is different from the invention in the Patent Document 1 in that the energy source capacitor is charged with full energy, and the load is driven only by the energy, and further, when the pulse is ended, the magnetic energy remaining in the load is recovered to the energy source capacitor.

In an example of Fig. 2, a load is an inductive load and is represented by a resistor R and an inductance L. In the case of gas laser, however, the load is a discharge electrode, and in the case of an accelerator bending magnet, the load is a dipole coil which is transformer-coupled. In both cases, the load is regarded as a load where L and R are connected in series. When the time of a discharge pulse is sufficiently shorter than the time constant  $L/R$ , the energy is mostly supplied by magnetic energy of the inductance.

An operating sequence of Fig. 2 is explained with reference to Fig. 3. Firstly a capacitor 1 is charged so as to have polarity of Fig. 2 (a charging circuit is not shown), and when switches S1 and S2 are turned on, electric charges of the capacitor start to flow to the load. When an electric current becomes maximum and the voltage of the capacitor is negative (forward-direction voltage of a diode), the load current reflows via the diode and is brought into a freewheeling state, and the load current continues to flow in two parallel lines in a direction where "a path where a main current flows" is written. The characteristics of the switch constitution and the operation are that the electric current in the freewheeling state continuously flows in two parallel lines. As a result, a current carrying capacity of the switches is only half, and thus this example is economical.

When the switches S1 and S2 are turned off, the electric current in the freewheeling state is cut off, and the capacitor 1 is recharged into the same polarity via two diodes. As a result, the electric current is quickly reduced and when it becomes zero, the diodes prevent reverse current, thereby stopping the electric current.

After the switches S1 and S2 are turned on, when anyone of the switches S1 and S2 is turned off while the capacitor voltage remains, the load current is brought into the freewheeling state, and the capacitor voltage is maintained. When the switch is turned on again, the electric current restarts to rise. The high-speed on/off operation of the switches possibly enables PWM control of the capacitor discharge current. This function cannot be realized by the simple current switches of the snubber recovering system.

When the switches and the diodes in the constitution of Fig. 2 are used, discharge can be started, maintained and reduced by turning on/off the switches at arbitrary timing. Further, the magnetic energy with the same polarity is recovered to the capacitor.

Fig. 4 is a principle diagram for developing the present invention in both directions of the electric current.

A difference of this drawing from Fig. 2 is that four units where diodes and switches are connected in parallel are installed in inverse-series and in inverse-parallel as shown in Fig. 4, so that a bidirectional electric current is allowed to flow in the load. The same point is that when the switches are turned off, the magnetic energy is recovered to the capacitor 1 (as in Fig. 2, the charging circuit is not shown).

In order to change the direction of the electric current to the load, selection from an operating switch group is brought into a "cross state", namely, the switches S1 and S2 are turned on in a current forward direction and the switches S3 and S4 are turned on in a current backward direction. "A pair of the switches are selected in the cross state" means that when the four switches are arranged into a quadrangular shape, two of them positioned on a diagonal line are selected. A rational design is made preferably in a manner that the switches and capacities of the diodes according to a level of the maximum electric current in the forward and backward directions are selected.

The table below indicates the ON/OFF states of the pair of switches S1 and S2 and the pair of switches S3 and S4.

Pattern	Pair		Pair		Remarks
	S1	S2	S3	S4	
1	ON OFF	ON OFF	OFF ON	OFF ON	When one pair is simultaneously ON, another pair is OFF.
2	ON OFF	OFF ON	OFF OFF	OFF OFF	When one switch of one pair (S1, S2) is alternatively ON, another pair (S3, S4) is always OFF.
3	OFF OFF	OFF OFF	ON OFF	OFF ON	When one switch of one pair (S3, S4) is alternatively ON, another pair (S1, S2) is always OFF.

Fig. 5 is a diagram illustrating a simulation circuit showing that the energy source capacitor 1 can be replenished with energy by a low-voltage large-current power supply 5 inserted into the discharge circuit, and a waveform as its result. According to the waveform of Fig. 5, the capacitor voltage and the load current rise according to the number of discharges, but this is because when a voltage which is not less than a voltage of a DC resistance is injected from an external power supply, the discharge current rises. When the voltage of the external power supply is increased or decreased in such a manner, the value of the pulse current can be controlled.

Prior to the operation, when a voltage is applied to a circuit by the low-voltage large-current power supply 5, an electric current which is determined by a resistor flows. Since the magnetic energy is recovered to the capacitor 1 and the capacitor 1 is charged by cutting off the electric current using a current switch, the pulse current for high-speed boot can be obtained only by the low-voltage power supply without preparing a high-voltage power supply for charging the capacitor.

Fig. 1 is a circuit diagram illustrating an embodiment of the present invention. A difference of Fig. 1 from Fig. 4 is that when an accelerator bending magnet 6 as a concrete example of a load is excited by a pulse current via a current transformer 3, four power MOSFETs are connected in inverse-series and in inverse-parallel. As a result, the four power MOSFETs compose a bridge circuit.

It is assumed that power MOSFETs used here are made of silicon carbide (SiC), and are quickly turned on/off with high withstand voltage, have less conducting loss, and can effectively utilize body diodes (also called parasitic diodes) as a substitution of parallel diodes.

Even when present power MOSFETs made of silicon which cannot practically use body diodes are used, they can be used by forcibly bringing them into an ON state by means of gate control when they are in an inverse conducting state. An inverse conductive type GTO thyristor or a unit in which diodes are connected to semiconductor switches such as IGBT and the like in parallel can produce the effect of the present invention.

In the present invention, a switch, which prevents an electric current from flowing in a forward direction when the switches are off but conducts in a backward direction, is called an inverse-conductive type semiconductor switch. Its examples are the power MOSFET, the inverse-conductive type GTO thyristor, and the unit in which the diodes are connected to the semiconductor switches such as IGBT and the like in parallel.

A gate signal is supplied to the power MOSFET switches G1 to G4 from a control device 7 shown in Fig. 1. A pair of the switches G1 and G2 are selected in a cross state so that a direction of the electric current is a forward direction, and when a pair of the switches G3 and G4 are selected, the direction of the electric current is the backward direction. This is necessary for enabling a flow of a magnetization reset current for

improving an exciting property of a current transformer for pulse operation of a compact medical accelerator bending magnet.

In Fig. 1, a low-voltage large-current power supply 5 is inserted between an inductive load 6 and the switch 2, and when its voltage is applied to a discharge current in series, energy can be replenished at every discharge. Further, at the first time, the low-voltage large-current power supply 5 allows an electric current 4 in the circuit, and by cutting off the electric current 4 by the current switch 2, the capacitor 1 can be charged like a snubber capacitor, and thus a pulse current for high-speed boot can be obtained only by the low-voltage power supply without preparing a separate high-voltage power supply for charging the capacitor. Needless to say, a general method of connecting a charging power supply to the capacitor 1 so as to charge the capacitor is effective.

## INDUSTRIAL APPLICABILITY

According to the present invention, the gate signals of bidirectional current switches having a bridge constitution composed of four semiconductor switches connected to diodes in parallel as the switch of the energy source capacitor for generating an electric current are controlled, so that the electric current to the inductive load can be started, maintained and stopped at a high speed. At this time, when the electric current is reduced, the magnetic energy is ~~re-generated~~ recovered with the same polarity as that of the capacitor. As shown in Fig. 5, when the low-voltage large-current power supply 5 is inserted into the current circuit, the charging voltage of the capacitor can be increased or decreased while a discharge cycle is being repeated.

When the two power MOSFETs in series have the withstand voltage, a total capacity of the four switch elements may be basically half, and further when it is considered that a pulse conductive current flows in two arms in parallel, the total capacity is half. For this reason, the present invention can be applied basically without increasing voltage-current capacity in comparison with conventional pulse power supply.